Load sensors for the LHC Low Beta Quadrupoles – design and validation

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Abstract:
The superconducting low beta quadrupoles of the LHC provide the final focus for the four main experiments. Tight alignment tolerances are therefore imposed and the positions of quadrupoles have to be monitored for possible adjustments with resolution of 10 µm. As the low beta quadrupoles are located in a highly radioactive area, they have been equipped with alignment monitoring systems and motorized supporting jacks for their remote adjustment.
Because of additional constraints added to the cryostats (bumpers, tie rods, friction), the contact between jack and cryostat can be lost during the repositioning. This could cause damages on the cryostats and interconnections. In order to realign safely these critical LHC components during accelerator lifetime – the jacks have been equipped with strain gauge washer type sensors to monitor vertical supporting jacks contact quality.

This paper presents firstly the technical requirements concerning sensors and data acquisition electronics. It introduces secondly the solutions studied and describes finally the solution chosen and installed (with the associated latest performance).

1-Introduction

The superconducting low beta quadrupoles of the Large Hadron Collider (LHC) provide the final focus for the four main experiments in the LHC (ATLAS, CMS, ALICE and LHCb). Each side of experiment is equipped with three of these magnets (Q1, Q2, Q3 – Fig.1), called *Inner triplet*. The position of each individual quadrupole is determined in five degrees of freedom, with a combination of two monitoring systems: The Wire Position System (WPS) and the Hydrostatic Leveling System (HLS).

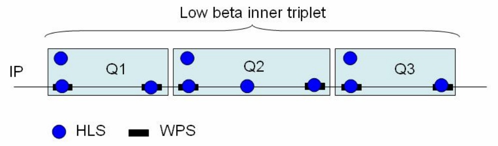

Fig.1. Inner triplet of right side of experiment (Interaction Point – IP)

When the deviations with respect to a reference position becomes greater than a given threshold, it is possible to move each cryostat to this reference position using the motorized jacks (Fig.2, Fig.3) [1].

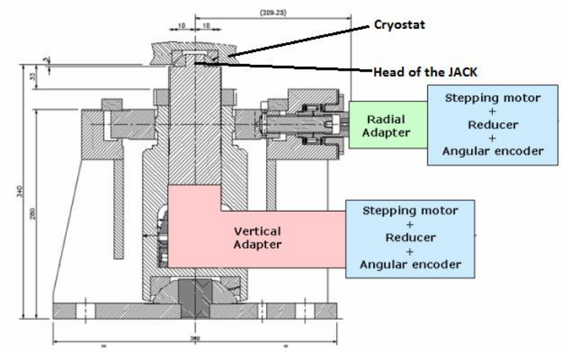

Fig.2. Elements of realignment and position control system

Fig.3. Operating principle of motorized jack

During repositioning, the contact between the cryostat and the head of one jack can be lost. This could be the cause of disastrous damages to the magnets at the level of the interconnections between the magnets. In the worst case they could even fall down. This problem was discovered in February 2011, during the realignment of one Q3 quadrupole. Remote alignment commands were sent for a radial displacement of 25 µm but they provoked suddenly a movement of 800 µm in radial direction and 400 µm in vertical direction. After investigation, the explanation was found that constraints coming from interconnections, as for example stacked stress of the tie rods, bumpers and spring as well as support friction, caused the loss of contact between the cryostat and the jack during a previous vertical alignment. This caused the cryostat moving at the radial iteration of the alignment process. As this problem has not occurred before, the operators were not even aware of the probability of such an event.

As solution to this problem it was proposed to install load sensors between cryostats and jacks in order to control the applied load at each contact point. This provides information of the weight applied on each jack to the operators and then consequently allows choosing a repositioning procedure that reveille in real time changes of the load distribution.

2-Requirements

In total 80 sensors will have to be installed on the vertical supporting jacks including cabling and control electronics.

Due to the high radiation level in the low beta quadrupoles areas with an expected ~16 kGy/year [1], the load sensors have to be radiation hard, the conditioning electronics have to be installed in a safe, radiation protected area and the cables connecting each sensor to electronics also must be radiation hard.

The given mechanical design of the jacks implies that the sensors have to be fitted into a small cylindrical space with a maximum diameter of approximately 70 mm and a height of 16,5mm.

To avoid big long term drift (creeping) on the sensor signal, the maximum operating force of the sensors was selected to 200 kN. This ensures approximated operating point of the sensors at the level of 25% of the maximum load.

The installation of the sensors should be plug-and-play without any complicated activities like machining, dissembling and assembling of several components. The integration with existing control system had to be assured. In the long term, the maintenance of the sensor has to be easy to handle.

The sensor does not need a high resolution. For system purposes a resolution of about 100 to 300 N and precision of about 500 to 1000 N is sufficient. More important is the long term stability of the sensor's shape, in order to prevent plastic deformation of the material and to guarantee output signal stability. The impact of length of the sensor cables, which can be up to 270 m, has to be taken into consideration.

The reduction of the overall system cost was also taken into account keeping in mind the priorities mentioned above.

3-Studied solutions

After a market analysis of accessible technologies and component prices it was decided to perform the tests of three different types of sensors and three different electronic conditioners:

a) The HMB KMR100 sensor (S1) is an off the shelf, strain gauge sensor with off the shelf conditioner HBM AE301 (E1) (washer type – Fig.4). Sensor and conditioner are manufactured by HBM company. This washer type sensor has compact dimensions which allow an easy integration into the jack. HBM declared also the ability to prepare a radiation resistant sensor version.

Fig.4. HBM KMR100 sensor

b) In accordance with the requirements of an easy integration into the existing control system and the reduction of electronics costs, a home-made strain gauge sensor conditioner (E2) solution was developed. The conditioner was tested with the HBM load sensor (S1) to compare performance of the sensor-cable-conditioner configuration with respect to industrial solution.

c) Two types of home-made Linear Variable Differential Transformer (LVDT) based membrane sensors (S2 - Fig.5, S3 - Fig.6) and special electronic conditioner (E3) were developed. The advantage of these solutions was the reduction of cabling costs whilst keeping measurement accuracy for long cable lengths. All signals of the sensors at one IP side could be sent by one multiconductor, externally screened cable. A similar solution was introduced at CERN to control collimator positions [2].

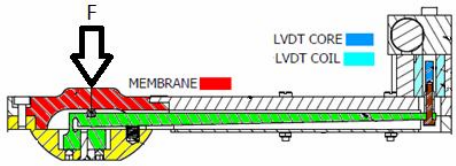

Fig.5. LVDT lever sensor

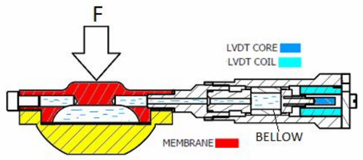

Fig.6. LVDT hydraulic sensor

4-Solution selected

4.1-Sensors

To carry out performance tests of the different combinations of load sensors and conditioners a special test bench was designed and manufactured (Fig.7).

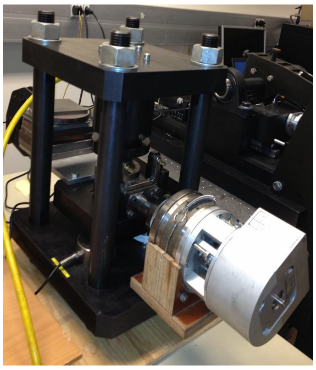

Fig.7. Load sensors test bench

The test bench allowed measuring different parameters as the conditioner's output signal and deformation as a function of the applied load and the ambient temperature.

Best overall performance showed the strain gauge type sensor (S1). The tested HBM KMR100 (Fig.4.) force washer sensor observed linearity and repeatability for a single sensor mounting position to better than 1% of maximum sensor load. However change of sensor mounting position (rotation around center hole) decreased its repeatability to 10%. That effect is linked with different sensor interface surface contact conditions for different positions.

The solution to keep repeatability at a level of better than 1% was to embed the sensor between two interfacing hardened washers oriented always in the same way with respect to the sensor (hardness > 40HRC, Ra < 1.6, flatness < 20 µm).

The solution based on LVDT gauges (S2+E3, S3+E3) shows a very good performance of sensors signal conditioning. Internal LVDT gauge shift resolution with a 270 m long cable was at the level of 1 µm (expected for 50 N of load change), however the tests of the prototypes met problems with a scale ratio of membrane deformation versus a move of the LVDT gauge core. Also a plastic deformation of the membrane at a load of 100 kN was observed. As this solution would have needed further research and development towards final solution, the LVDT project was abandoned.

Based on preliminary test results for the KMR100 (S1), it was decided to order HBM MPZ1108010 force washer sensors (with maximum nominal force of 200 kN), specially designed for CERN specifications (Fig.7, Fig.8). The sensor dimensions were adapted to fit with the interface washers into the available space in the jack (Fig.9).

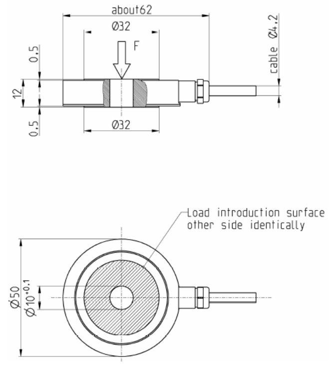

Fig.7. Rad-hard MPZ1108010, load sensor

Fig.8. MPZ1108010 sensor with interfacing hardened washers

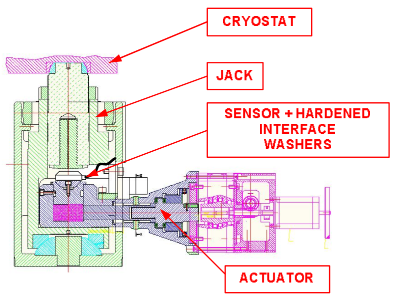

Fig.9. Vertical jack and sensor installation space

As this sensor was specially developed for CERN, it has to be considered and tested like a prototype. The MPZ1108010 force washer achieved a precision of 4 kN which corresponds to 2% of the sensor maximum force. The linearity of each sensor, in a single sensor mounting position, was at the level of 5% of the sensor maximum force. To improve sensor precision and obtain similar values as with the KMR100 sensor (S1), the MPZ sensors were always oriented in the same way with respect to the interfacing hardened washers. Figure 8 shows the interfacing washer attached to the sensor's body by using elastic glue. Hence a constant washer-sensor orientation is provided and the impact on the load measurements results is minimized. The problem of nonlinear characteristic of the sensors and the impact of the use of long signal cables (impedance effects) has been solved with an in situ and individual sensors calibration. The final precision of each calibrated sensor has been achieved at the level of 0.5 kN to 1 kN in the range of the sensor from 0 kN to 8 kN. In the range above 8kN, the precision decreased to a maximum of 3 kN.

4.2-Sensors signals conditioning

In consideration of the analysis of conditioners performance, accessible space in existing electronics racks, problems of effective and easy integration in the data acquisition system (CERN, *WorldFip* protocol based) – the home made strain gauge conditioner solution, used the popular Analog Devices AD7730 chip (E2) was selected. The prototype (Fig.10) tests resulted in a performance

similar to the tested off the shelf conditioner (E1). Tested with the same cable length of 270 m and the same sensor connected (S1), the noise of the output signal for both conditioners was at the level of 50 N with a resolution of 30 N.
The successful tests results of the prototype, lead to the conclusion that the home-made solution was well suited for the application. In consequence a 12 input channel acquisition crate, named Load Sensors Acquisition System (LSAS), was designed (Fig.11).

Fig.10. Home-made conditioner prototype (E2)

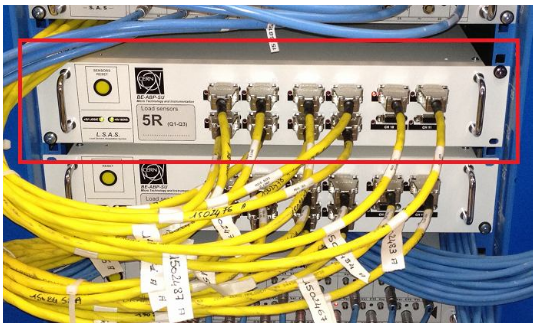

Fig.11. LSAS conditioning crate

An important role is played by the cabling concept in order to have high signal quality. Using strain gauges with the measurement principle of a Wheatstone bridge, the signal change at the Nanovolt level is significant. A noise robust and radiation-hard cable was needed; the solution was provided with the 3 three pair double shielded MBB6 DRAKA cable; the type of cable that has been chosen at the beginning for all force washer tests presented previously.

5-Final performance, conclusions

Currently 7 out of 24 cryostats are equipped with 23 sensors. The analysis of the measurement data showed high stability of sensors signal also during the operation of the LHC. Within the first two months of operation in constant conditions, the sensors do not show signal drift (creeping) greater than 200 N whilst being loaded at 25% of nominal force. The output signal noise increased to approximately 200 N for some cables. This can be linked to the use of industrial cable paths that are shared with other users and therefore create a noisy environment. One disadvantage of the concept is the need of in situ recalibrations of the sensors in the radioactive environment which is linked with the impedance effect on the measured sensor signal value due to the long cables.

References

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[2] A.Masi, A. Brielmann, R. Losito, M. Martino, LVDT Conditioning on the LHC Collimators, IEEE Transactions on Nuclear Science, vol. 55, NO. 1 (February 2008)